EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER
IN THE REACTING BOUNDARY LAYER ON A POROUS PLATE

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ABSTRACT. Intensive heat fluxes and high temperatures in
contemporary combustion chambers and heat exchangers cause
damage to the structural elements; the damaged elements can
enter into chemical reactions with each other or with the
external environment. In the present study, a special low
velocity wind tunnel containing a porous plate mounted on
the lower wall of the closed 280 X 340 mm test section was
used, with the air flow rate over the plate varying from 1
to 8 m/sec. Air temperature varied from 288 to 393°K.
Ethyl alcohol was used as the reacting liquid, injected
through the plate surface. The study showed that the heat
liberated during the chemical reaction was partially trans-
ferred to the plate, used to evaporate the reacting liquid,
and partially dissipated by the air flow. The heat and mass
transfer in the reacting laminar boundary layer are ana-
lyzed.

Porous, or evaporative cooling of various apparatus and devices is /37[1]
accompanied in certain cases by chemical reaction in the boundary layer. The
intensive heat fluxes and high temperatures encountered in modern combustion
chambers and heat exchange apparatus cause, as a rule, damage to the elements of
which these devices are constructed. The elements of the damaged surface may
enter into chemical reactions among themselves or with the surrounding medium.

Therefore, the most important problem at the present timme, a problem of
great practical significance, is investigation of the process of heat and mass
exchange in the boundary layer during chemical reactions.

There are a number of theoretical works dedicated to this problem, the most
complete review of which is presented in [1-7, 9, 10], whereas experimental
investigations are practically completely missing, with the exception of
[8, 11].

The main purpose of the experimental investigation of this process is the
establishment of the dependences between the surface temperature of the porous
metal plate, the temperature in the reaction zone, the position of the reaction
front and the expenditure by weight of injected fuel liquid, as well as a
determination of the concentrations and enthalpies in the reacting boundary
layer under various hydrodynamic and temperature conditions of the oncoming air

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[1] Numbers in the margin indicate pagination in the foreign text.

stream.

The experimental investigation of the process of heat and mass exchange in the reacting boundary layer was performed using a special experimental insulation (Figure 1), consisting of a low velocity, closed continuous operation wind tunnel with closed test section and rectangular cross section of 280 X 340 mm.

The porous plate being investigated was mounted in the lower wall of the test section of the wind tunnel.

The wind tunnel operated open, which was achieved by using special regulating valves. Operating the wind tunnel in closed circuit would result in the accumulation of a large quantity of reaction products in the tunnel and would introduce considerable errors to the determination of concentrations in the reacting boundary layer.

The air stream in the wind tunnel was moved by a type VVD-9 high pressure centrifugal fan, driven by a 27 kw electric motor.

In order to avoid the transmission of vibrations from the fan to the wind tunnel, flexible couplings connected both intake and output sections to the fan.

The velocity of the air stream approaching the plate, represented as u_∞, was 1-8 m/sec and was regulated by special valves.

The dynamic pressure head of the air stream was measured using combined Pitot-Prandtl tube pneumometric fittings plus a cup type, multirange liquid micromanometer with a type MMN inclined tube, accuracy class 0.5. The combined Pitot-Prandtl fitting is set up in the wind tunnel some distance upstream of the test section so that the measuring transducers will have no influence on the fitting. The air in the wind tunnel was heated by a four-section electrical heater of 55.2 kw power. The last section of the heater (furthest downstream) was connected to the automatic temperature regulation system, while the other three sections were connected individually into the electric power supply. The maximum power of the regulated section of the heater was 8.6 kw. The automatic regulating system consisted of a chromel-copel thermocouple, used as a temperature transducer, an automatic electronic regulating and strip chart recording potentiometer type EPD-12, class of accuracy 0.5, and an asynchronous motor with braked rotor used as a voltage regulator. The rotor was turned by a type PR-1 actuating mechanism. In this way, both "smooth" and "stepped" temperature regulation could be achieved automatically. The fixed air stream temperature in the test section was stable, deviations amounting to ±0.3°C. The wind tunnel was surrounded with multilayered heat insulation.
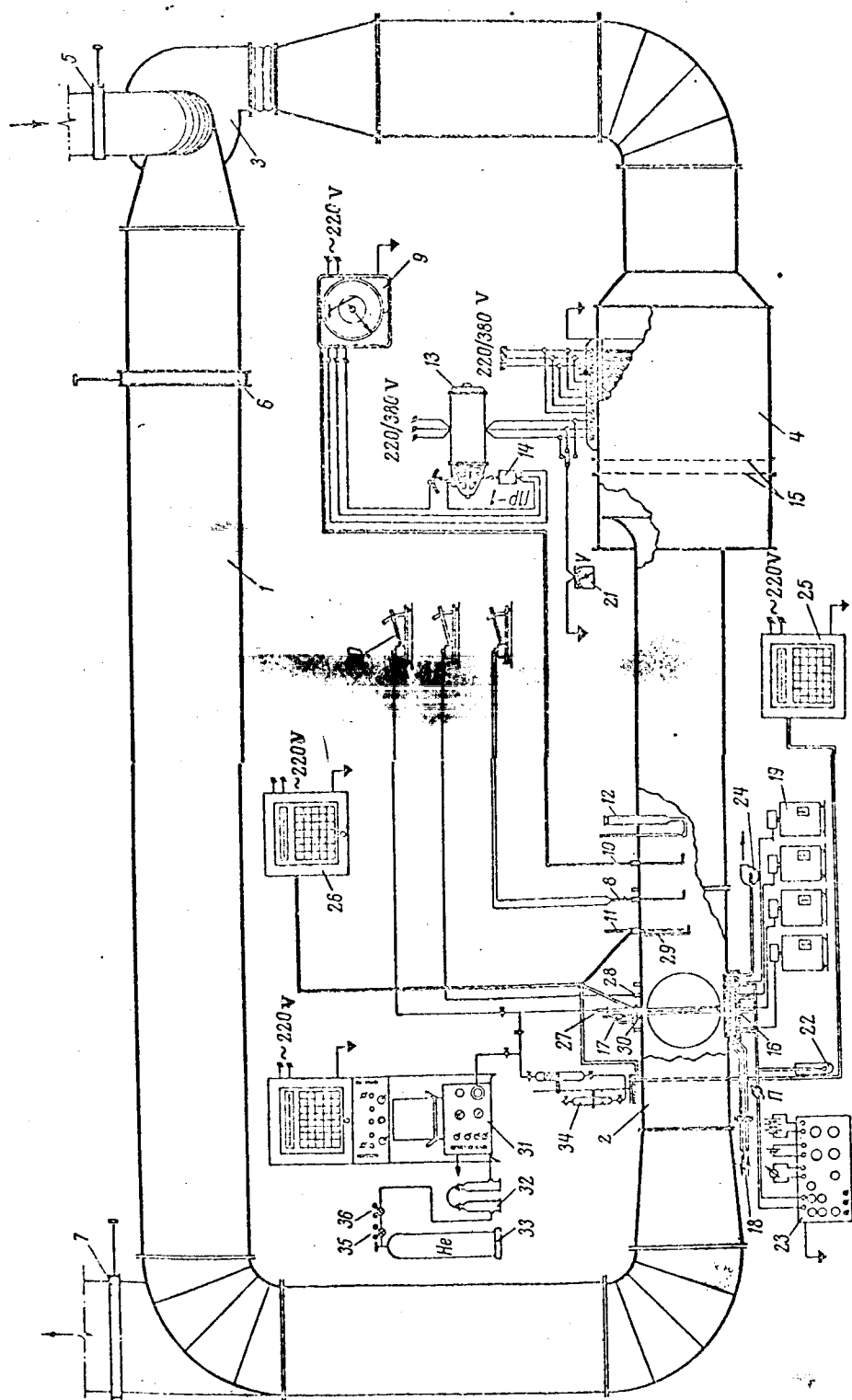
Figure 1. Diagram of Experimental Apparatus: 1, Closed wind tunnel; 2, Test section; 3, Fan; 4, Electrical heater; 5, 6, 7, Regulating valves; 8, Pitot-Prandtl tube; 9, Type EPD-12 potentiometer; 10, Temperature transducer; 11, Mercury thermometer; 12, Psychrometer; 13, Voltage regulator; 14, Actuating mechanism type PR-1; 15, Screens; 16, Test body; 17, Coordinator; 18, Cooling water supply; 19, VTK-500 weights; 20, MMN micromanometer; 21, Voltmeter; 22, Thermostat; 23, R-306 potentiometer; 24, Fan; 25, EPP-09 M3 potentiometer; 26, EPP-09 M1 potentiometer; 27, Dynamic pressure tubes; 28, Static pressure nipple; 29, 30, Thermocouples; 31, Type KhL-3 chromatograph; 32, Gas drier; 33, Helium cylinder; 34, System for flushing gas sample tubes; 25, 26, Pressure reducers: hydrogen and acetylene

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The temperature of the oncoming air stream, which varied between 288 and 393°K, was measured by copper-constantan and chromel-alumel theromocouples, the readings of which were recorded by type EPP-09 and EPP-09 M1 recording potentiometers respectively. The class of accuracy of these potentiometers is 0.5. Also, the air stream temperature was measured by a mercury thermometer with scale divisions each 0.1°C. Copper-constantan thermocouples in the vertical and horizontal walls and connected to a type EPP-09 recording potentiometer were used to measure the temperatures of the internal walls. The velocity and temperature of the air stream in the wind tunnel were stabilized by two screens placed 0.3 m from the heating unit, as well as a smooth convergent channel intake made in the form of a flat lemniscate located near the screens. The length of the stabilizing sector, i.e. the difference from the smooth intake to the test section of the tube, was 2.5 meters, which is sufficient for full equalization of the air flow.

In order to determine the evenness and stability of the air stream in the test section of the wind tunnel, both the hydrodynamic and thermal fields were carefully measured. Unevenness of the field of averaged velocities and temperatures in an area occupying over 80% of the test section did not exceed 1.5-2% of the air flow rate and temperature on the tunnel axis. The turbulence of the oncoming air stream was also measured using a type ATA-2 thermal anemometer with ac feedback, operating by the constant filament temperature method. A gold plated tungsten filament 0.018 mm in diameter and 3 mm long, with extremely high time constant of thermal inertia, was heated by high frequency alternating current.

The degree of turbulence of the incident air stream under the experimental conditions which we used was ϵ = 0.5%.

In order to facilitate visual observation of the process occurring in the reacting boundary layer over the porous plate, and also for convenience in servicing, windows of type LK-5 heat resistant glass 270 mm in diameter and hermetically sealed were placed in the side walls of the test section.

The reacting fluid injected through the surface of the plate was ethyl alcohol (C_2H_5OH).

The experimental body (Figure 2) was a porous metal plate 196 × 60 × 3 mm, divided into four sections. The first section was 30 mm long, the second was was 40 mm long and the last two were each 60 mm long. Each section of the porous metal plate was soldered to a nickel-plated brass body. In this way, complete hermetic sealing with the wall of the body was achieved, eliminating the possibility of fluid leakage.

The working plate was made using porous metal 3 mm thick, made of a spherical powder of chrome-plated low carbon steel, ball diameter 0.063 mm. The porous material used had good structural characteristics, even porosity throughout the entire mass of each specimen and good mechanical strength. The porous plates made from the 0.063 mm diameter fraction had an overall porosity of 11.7%, the mean pore diameter being 18 μ.
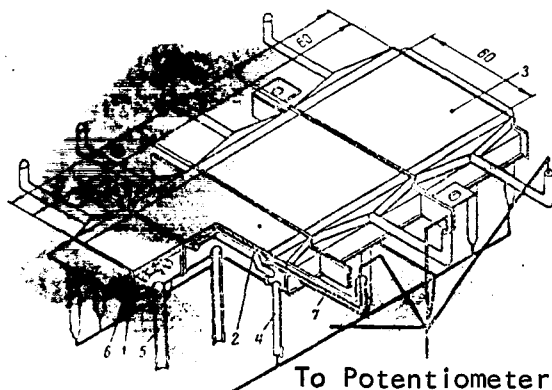
To Potentiometer

Figure 2. Experimental Body: 1, Nickel-
plated brass body; 2, Porous metal
plate; 3, Copper-constantan thermo-
couple; 4, Cooling water intake line;
5, Intake line for reaction fluid (ethyl
alcohol); 6, Textolite receiving pan; 7,
Air bubble drainage line

The air bubbles which formed beneath the plate were removed through special drainage tubes. The leads to the copper-constantan thermocouples mounted inside the experimental body as well as on the inner and outer surfaces of the porous metal plates came out through these same drainage tubes.

The fuel liquid was fed into each section through a special feed line. The ethyl alcohol flow rate in each section was recorded by the weight method using highly sensitive type PTK-500 electrical square balance with a scale division of 0.1 g. Connectors were made in the ends of each section of the porous plate to connect the rubber tube to graduated glass tubes, so that the level of the evaporation zone in the porous plate could be established visually, depending on the variations in hydrodynamic and temperature conditions of the experiment.

Under the conditions we used, the level of the evaporation zone practically corresponded to the surface of the porous plate. Since the experimental body and tank containing the reacting liquid and mounted on the VTK-500 balance actually amounted to connected vessels, the cross section of the tank was calculated so that as it moved upward with expenditure of the injectant, the pressure of the evaporating fluid remained the same and the level of the evaporating zone corresponded to the surface of the porous plate.

A 10 mm accumulating reservoir made of a heat insulating material was attached to the leading edge of the experimental body. The boundary layer was pumped off through a slit in front of the accumulating reservoir in order to exclude the influence of flow development.

The temperature of the surface of the metal porous plate was measured by copper-constantan thermocouples made of 0.15 mm diameter wire. The thermocouples were fastened into the porous metal plate by drilling holes, then drawing the wires through and welding them. The thermocouple head was placed in a hole of a diameter slightly less than the diameter of the wire junction. Then the head of the thermocouple was pressed into the hole and its face brought up /43 level with the surface of the experimental body. In all, 27 copper-constantan thermocouples were installed in the experimental body. Ten of the thermocouples were placed in a checkerboard pattern over the external surface of the porous

plate, four of these (one thermocouple in each section) being connected to a type R-306 low resistance laboratory dc potentiometer, the others -- to the EPP-09 potentiometer. Thus, double control of the temperature measurement of the porous plate surface was achieved. One thermocouple was placed on the outer side of the porous plate in each section, and thermocouples were also placed within the depth of the porous plates. The temperature of the fuel liquid was measured at the intake to the porous plate in each section by copper-constantan thermocouples. The temperature of the cooling water passing through the coolers was measured at the intake and output to each section with copper-constantan thermocouples, the indications of which were recorded by an R-306 low resistance laboratory potentiometer. The cooling water was fed into each section from the water supply line through a distributing manifold. Stopcocks were placed in each rubber supply hose, allowing the cooling water flow and, therefore, the temperature of the reacting liquid, to be controlled. The cooling water flow rate through each section was determined by measurement.

The mean surface temperature of the porous plate was calculated from the measured local temperatures for each sector of the section. The parameters of the boundary layer -- velocity, temperature and concentration -- were measured simultaneously at one point, since the dynamic pressure tube (also used to remove samples for concentration determination) was combined with a chromel-alumel thermocouple, wire diameter 0.15 mm into a single measurement probe. In order to avoid catalytic phenomena, the chromel-alumel thermocouple was covered. The measuring probe was moved both longitudinally and transversely by the coordinator, a micrometric screw with a scale division of 0.01 mm.

The velocity in the boundary layer was measured by the dynamic pressure tube and static pressure measurements. The dynamic pressure tube, made of stainless steel, had a tip with an internal diameter of 0.43 mm. The static pressure in the experimental apparatus was measured through 0.35 mm apertures drilled in the lower and side walls of the test section of the wind tunnel. The indications of dynamic and static pressure were recorded by a cup type, multi-range type MMN micromanometer.

The profile of concentrations in the reacting boundary layer was determined by taking gas samples. The gas sample collectors were made of stainless steel, with the 0.43 mm aperture expanding quickly to a diameter of 2.5 mm, in order to damp chemical reactions in the volume of the gas samples. A cooling system was provided for the sample tube, consisting of a water jacket around the 2.5 mm diameter dynamic pressure tube. The water jacket also carried a second tube of the same diameter, through which the cooling water circulated. The cooling water was drained through a fitting welded into the water jacket.

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Analysis of gas samples was performed at room temperature; consequently, stable molecular materials were obtained, such as carbon dioxide (CO_2), oxygen (O_2), carbon monoxide (CO), nitrogen (N_2), the sum of hydrogen plus saturated hydrocarbons ($H_2 + C_nH_{2n+2}$). Gas samples were taken from the gas sample tubes using a medical syringe, sample volume being not over 1-1.5 cm^3.

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Before a gas sample was taken and during collection of gas samples, the gas sample tube system was blown through by a special flushing system consisting of two burettes, rubber tubes and regulating valves. Analysis of the gas samples taken from the reacting boundary layer was performed using a type KhL-3 laboratory chromatograph.

The KhL-3 chromatograph used helium as the carrier gas, drawn from a 150 atmosphere pressure cylinder. Smooth reduction of the high pressure from 150 atm. to 1.5-2 atm. was performed using two reducing valves, one hydrogen valve and one acetylene valve, installed on the pressure cylinder, with final fine regulation of pressure by a needle valve. The necessary flow rate of the carrier gas was checked using a wet test meter. To help in deciphering the chromatograms, the device was calibrated for the gases being determined. Simultaneously with measurement on the KhL-3 laboratory chromatograph, gas samples were analyzed using a type VTI-2 gas analyzer (GOST 5433-56). The error in analysis of the bas samples with the type VTI-2 gas analyzer does not exceed ±0.1%.

Figure 3 shows the distribution of temperature T and concentration by sections in the reacting laminary boundary layer over the porous metal plate upon injection of the fuel liquid. The reacting fluid (ethyl alcohol) is a hydrocarbon; therefore, its boiling point is considerably lower than the temperature corresponding to the beginning of the reaction. Since during the experiment the temperature of the surface T_w of the porous metal plate on the upstream end was equal to or slightly greater than the boiling point of the reacting fluid, the reaction zone or front could not be located on the plate surface. Consequently, the chemical reaction must occur in the gaseous phase, and the reaction front is located some distance from the surface of the metal plate.

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The position of the chemical reaction front η_* is characterized by the fact that the vapors of the reacting liquid and oxygen approach the reaction zone from opposite directions.

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Measurement of the temperature in the reacting boundary layer over the porous metal plate showed that the reaction front separates from the surface of the porous metal plate as we move downstream.

The oxygen (O_2) diffuses in the direction of decreasing concentration, i.e. from the external flow to the chemical reaction front, where it is almost completely expended. Oxygen still penetrates to the surface of the porous metal plate, since its concentration at the surface of the porous plate was never equal to zero. The carbon dioxide (CO_2) formed during the course of the chemical reaction diffuses from the chemical reaction zone into the external air flowand down to the porous wall. In area I, i.e. between the surface of the porous metal plate and the reaction front, vapors of the reaction liquid diffuse toward the reaction front, where they are almost completely expended. Due to the fact that the content of O_2 in area I is slight, the CO_2 probably reacts
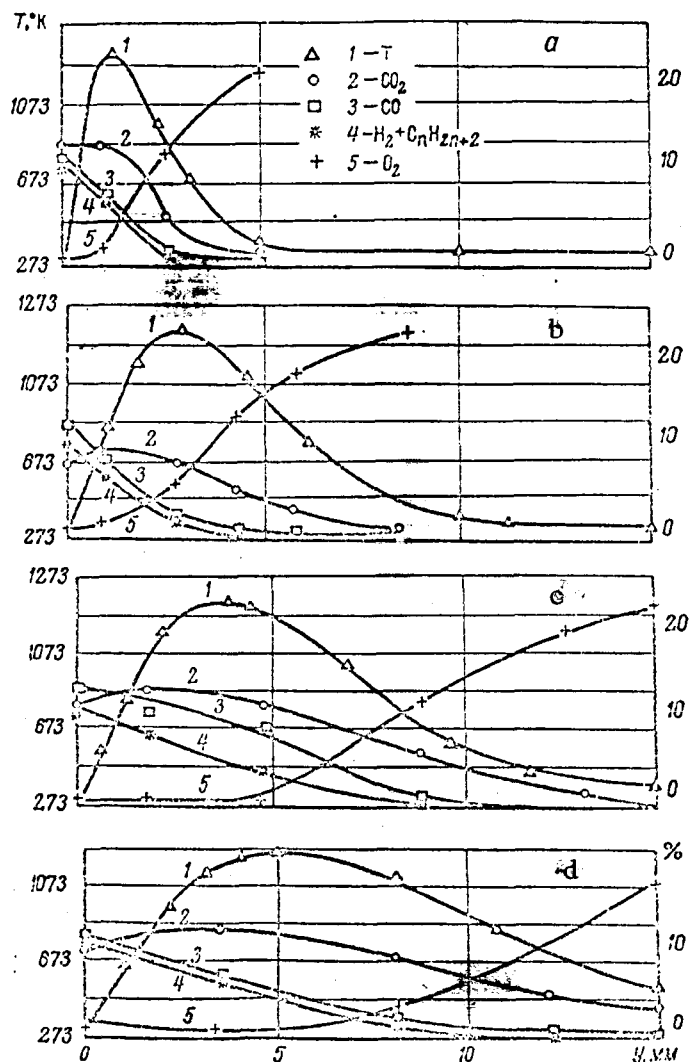
Figure 3. Distribution of Temperature and Concentration by Height in Reacting Boundary Layer: $T_\infty = 303°K$; $Re_\infty = 0.4 \cdot 10^5$; reacting fluid, ethyl alcohol; a, Section I, x = 25 mm; b, Section II, x = 62 mm; c, Section III, x = 114 mm; d, Section IV, x = 176 mm

with the vapors of the reacting liquid, as a result of which CO is formed, which diffuses to the front of the chemical reaction. In this same manner, H_2 can be formed, the concentration of which in area I is slight. In spite of the fact that neither carbon monoxide nor carbon dioxide are formed on the surface of the porous plate, their concentration at the porous plate surface is noticeable, due to the factors outlined above.

The heat liberated during the chemical reaction as the vapors of the reacting liquid burned is partially conducted to the surface of the porous plate and expended in heating the framework of the plate and evaporating the reacting liquid. The remaining portion of the heat is carried off in the external air stream.

As we can see from Figure 3, the position of the chemical reaction front can be determined from the maximum temperature in the reacting laminar boundary layer.

On the basis of the above, we can conclude that the process of heat and mass exchange in a reacting laminar boundary layer occurs as follows:

a) the reaction front is a thin zone (surface) located in the boundary layer at some distance from the porous surface (at the leading edge of the

experimental body $\eta_* = 0$). The value of η_* depends on coordinate x, i.e. $\eta_* = \eta_*(x)$;

b) in the zone between the reaction front and the plate (area I) the concentration of oxidizer (in this case oxygen) is slight. In area II (between the reaction zone and the external edge of the boundary layer) the mass content of fuel liquid vapor is also slight; /47

c) throughout the volume of the boundary layer, we find inert components (N_2) and reaction products (H_2O vapors, CO_2);

d) the carbon monoxide content is finite at the surface of the body and decreases monotonously, reaching practically zero at the reaction front; the formation of CO[1] in this area results from the reaction of the ethyl alcohol vapors and carbon dioxide under oxygen-deficient conditions;

e) analysis of Figure 3 shows that the position of the reaction front η_* corresponds to the maximum temperature in the reacting laminary boundary layer and the minimum concentration of fuel liquid vapors.

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[1] Original Russian document says "the formation of CO_2 in this area ..." obviously a misprint -- Tr.